Neutral Currents: Experimental Results at High and Intermediate Energies

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Physics Beyond the Standard Model

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Update on high Q^2 events at HERA

Is a corresponding high-E_T excess seen in $\bar{p}p$ collisions?
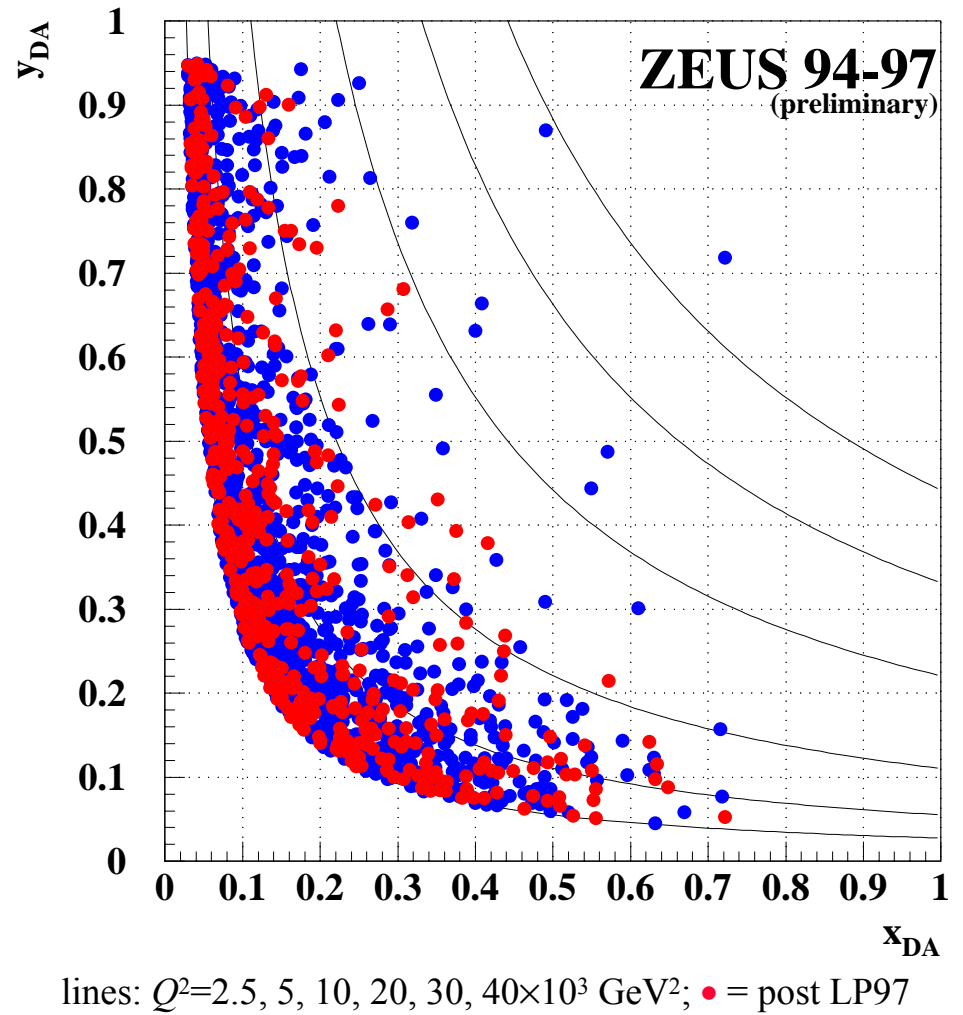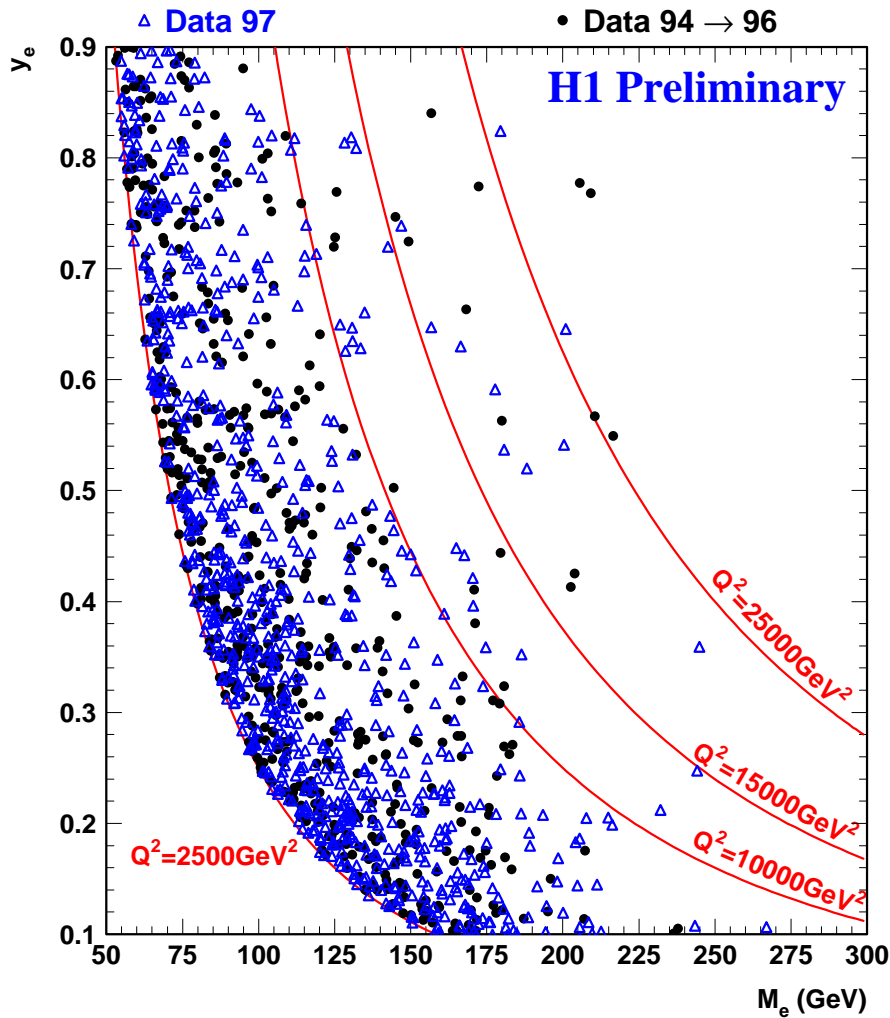
Limits on first-generation leptoquarks

Limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings

Limits on Z' mass and mixing in extended gauge models

Limits on contact interactions

URL for this talk: `http://www-d0.fnal.gov/~strovink/`

Update on high Q^2 events at HERA

lines: $Q^2=2.5, 5, 10, 20, 30, 40\times10^3$ GeV^2; ● = post LP97

In early 1997, H1 and ZEUS reported excesses of high Q^2 NC events with respect to SM expectations. The extra events appeared in two disjoint regions of $M_{ej} \propto \sqrt{x}$; the H1 excess was clustered near $M_{ej} = 200$ GeV. The fluctuation probabilities were of order 1%.

Data collected by H1 in 1997 (△), and by ZEUS in the last half of 1997 (●), did not confirm these excesses.

Update on high Q^2 events at HERA (cont'd)
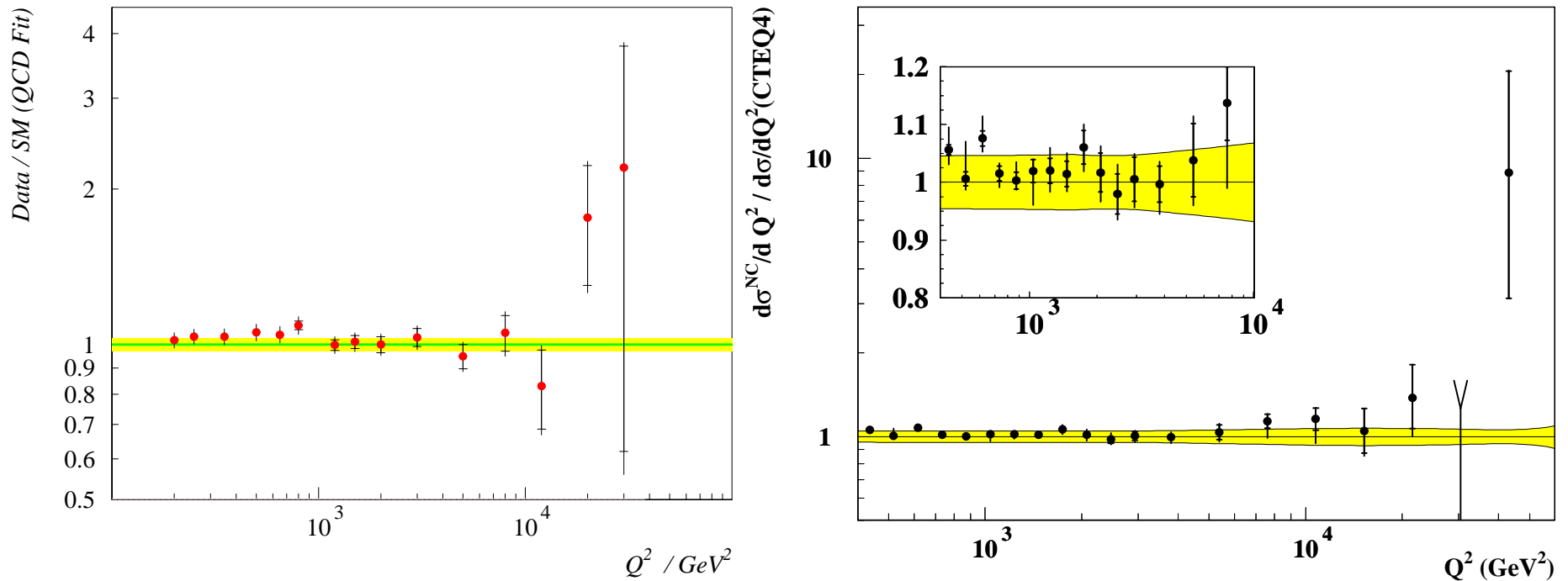
The full 1994-7 H1 (left) and ZEUS (right) preliminary datasets, when compared to DIS expectations, show residual excesses at highest Q^2, but the significances of these excesses are reduced compared to the 1994-6 data alone.

Q^2(min)	------ H1 ------			---- ZEUS ----		
(GeV^2)	expected	seen	P($\geq N_{obs}$)	expected	seen	P($\geq N_{obs}$)
5000	336	322	0.560	396±24	440	
10000	55	51	0.600	60±4	66	
15000	14.7±2.1	22	0.059	17±2	20	
20000	4.4±0.7	10	0.018			
25000	1.6±0.3	6	0.006			
35000				0.29±0.02	2	~ 0.035

Update on high Q^2 events at HERA (cont'd)
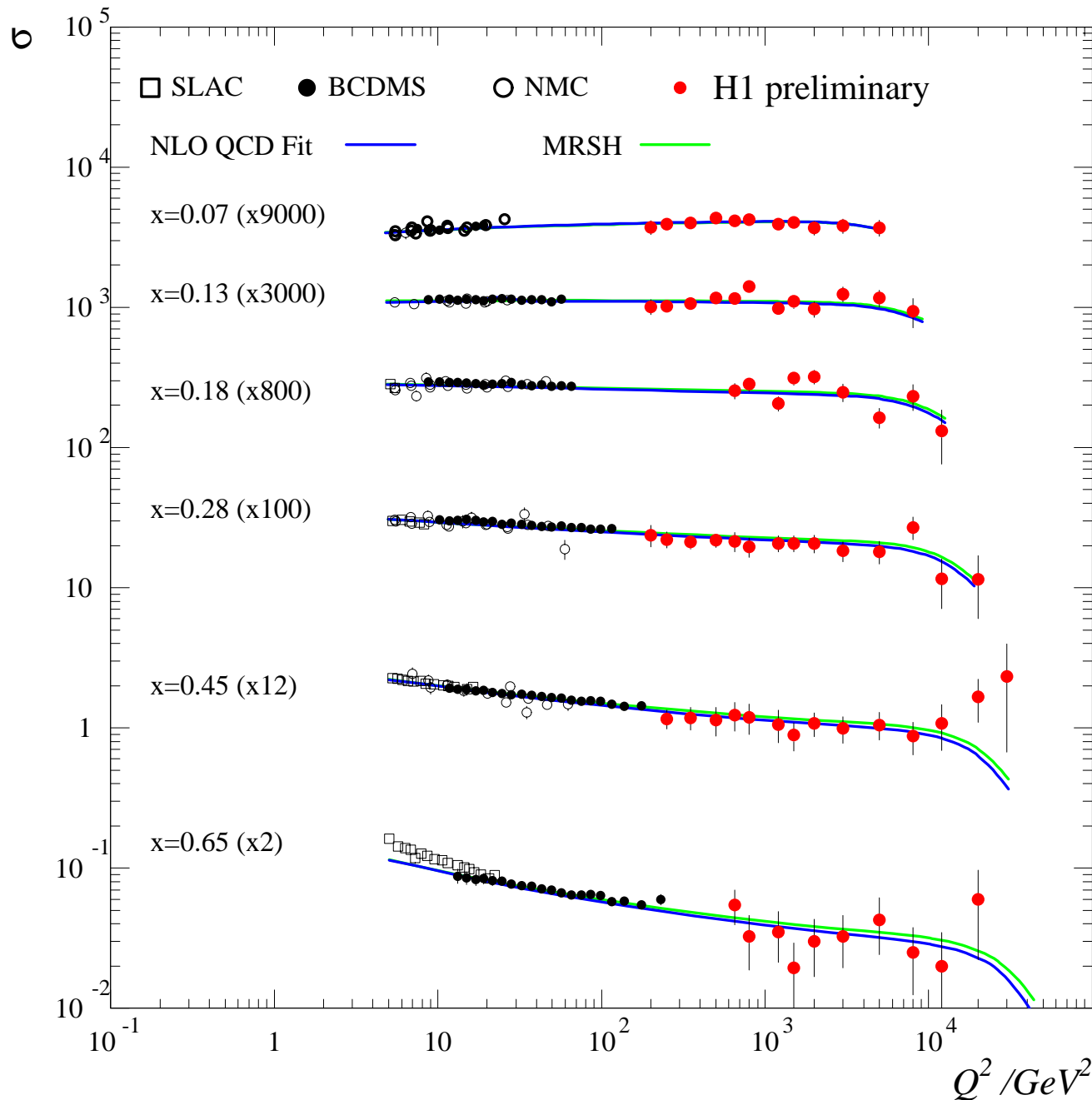
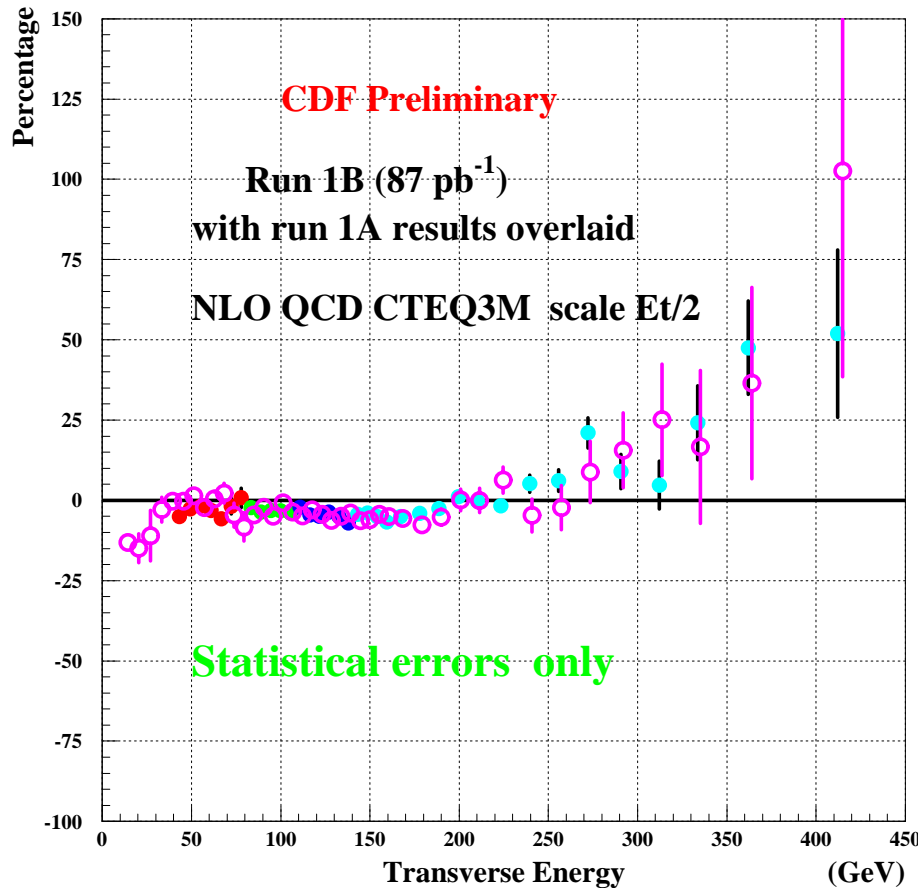The high x HERA NC data match smoothly to structure functions determined by ep and μp scattering in fixed target experiments.

Shown is the current H1 determination of σ, [equal to the cross section differential in x and Q^2, multiplied by kinematic factors so that $\sigma = F_2$ if F_L, and the parity violating term F_3 from Z^0 exchange, are ignored]. Seen are the expected γZ interference and high-x nonscaling.

Including the full H1 dataset in an NLO QCD fit pulls σ below the MRSH extrapolation at high Q^2.

Is a corresponding high-E_T excess seen in $\bar{p}p$ collisions?

CDF Preliminary

Run 1B (87 pb^{-1})
with run 1A results overlaid

NLO QCD CTEQ3M scale Et/2

Statistical errors only

Above are CDF's (data-CTEQ3M)/CTEQ3M points, from Run 1A (published, o) and 1B (preliminary, •). Errors are statistical.

CDF concludes that standard PDFs (like CTEQ3M) require modification.

They provide an analytic function passing smoothly through their points.
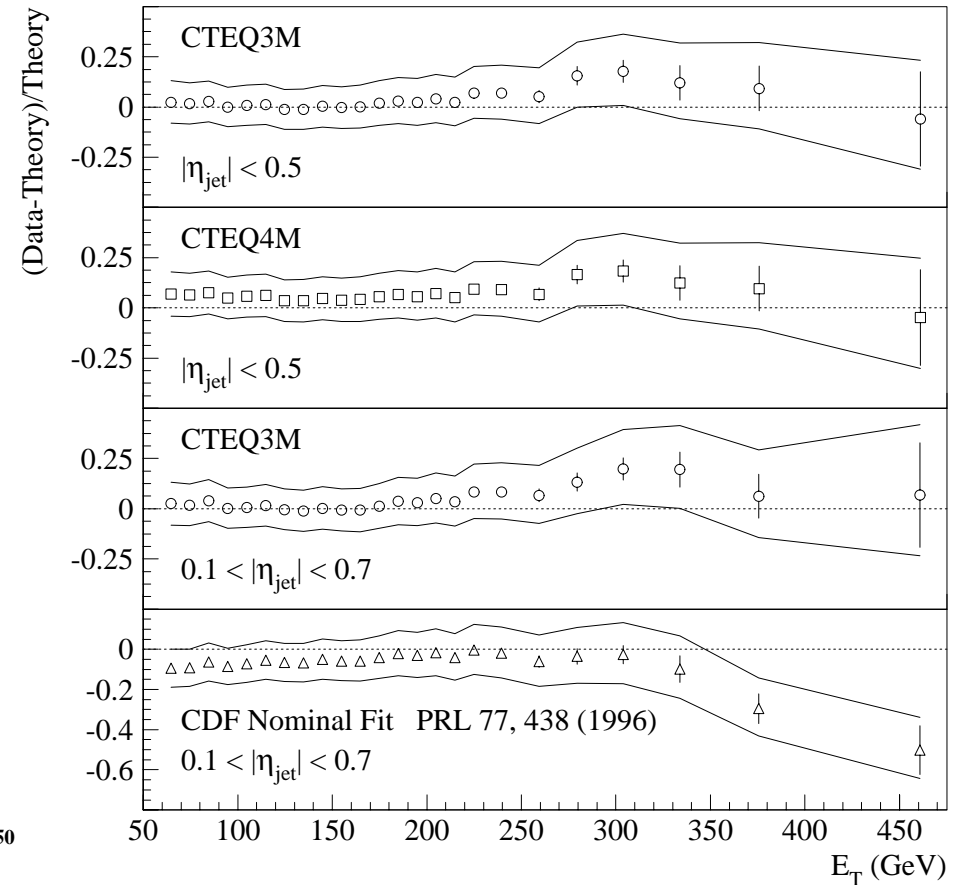
D0's Run 1B data are compared above to standard PDFs and also to CDF's function. The systematic error bands are parametrized by a covariance matrix.

The standard PDFs give acceptable χ^2 values, but the χ^2 probability for CDF's function is of order 10^{-5}.

Limits on first-generation leptoquarks
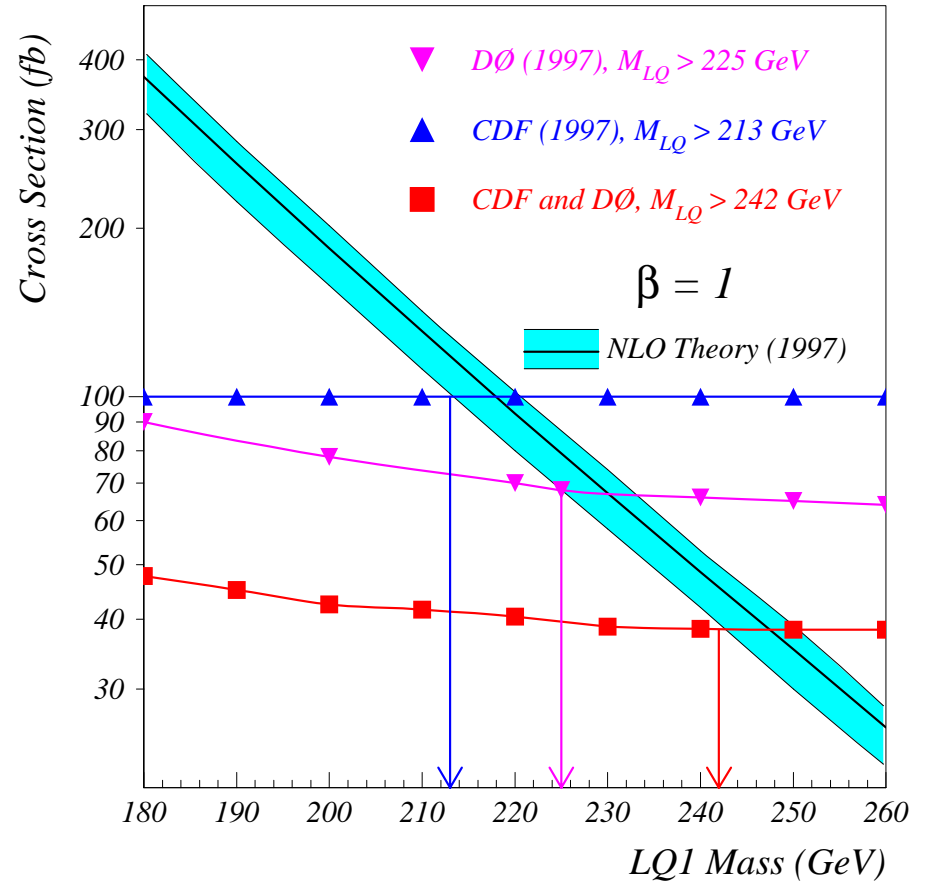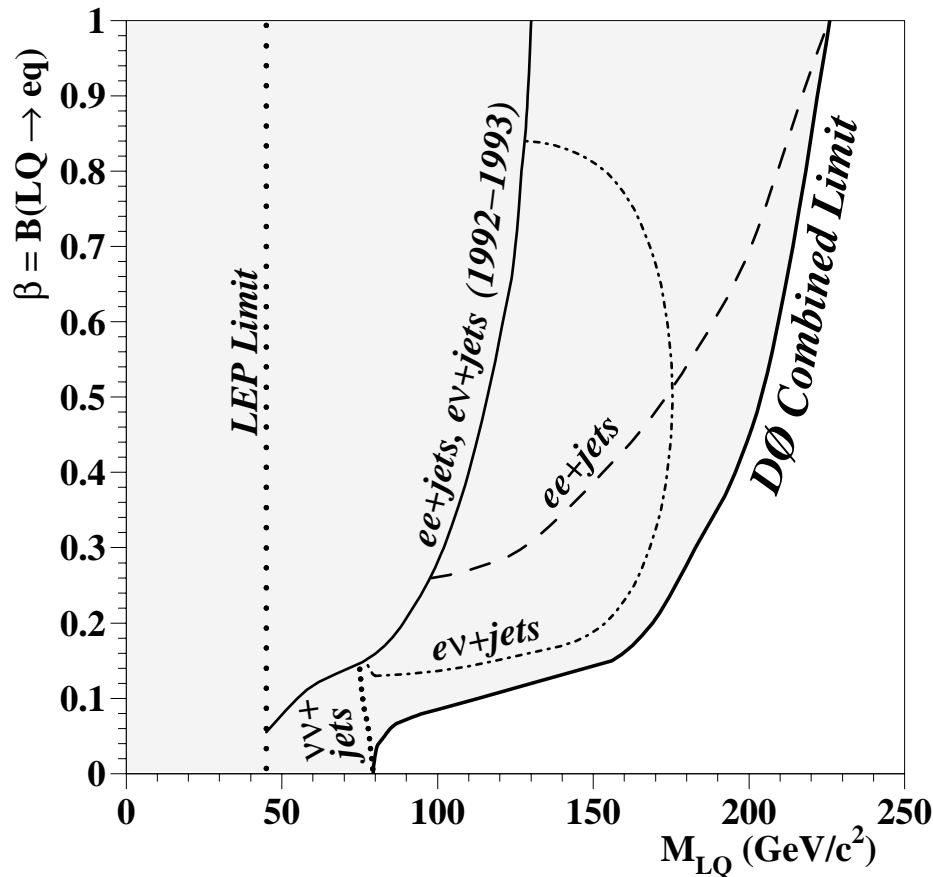
If first-generation leptoquarks were to exist, the new interaction that would bind e to q would enhance eq scattering near the LQ_1 mass (~ 200 GeV, suggested by 1994-6 H1 data).

At the Tevatron, LQs could be pair produced strongly, independent of the e-q coupling.

Shown at left is D0's published scalar LQ_1 mass limit vs. $\beta = BR(LQ_1 \rightarrow eq)$. For $\beta = 1$, $M(LQ_1) > 225$ GeV. Additional points from CDF are at 213 (180) GeV for $\beta = 1$ (0.5).

At right, CDF and D0 combine their ($LQ_1 \rightarrow eq$) search to limit $M(LQ_1) > 242$ GeV at $\beta = 1$.

Limits on first-generation leptoquarks (cont'd)

Yang - Mills Exclusion Contours

V_{LQ} Exclusion Contours
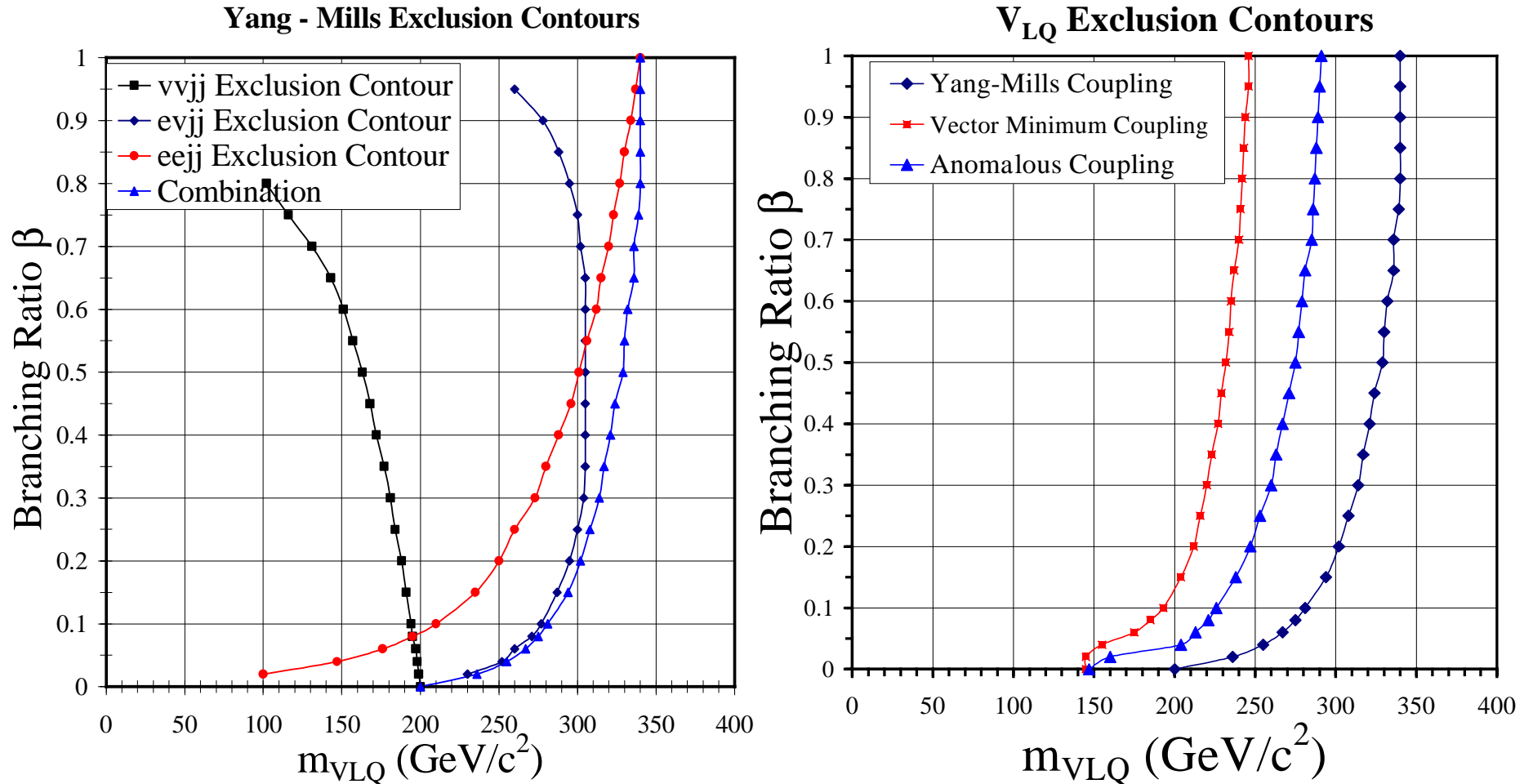
Recently D0 completed a similar search for vector leptoquark pair production. Again the combined limit contours vs. β are the result of separate analyses (left) in the *eejj*, *evjj*, and *vvjj* channels.

The D0 combined limit contours are presented (right) for 3 choices of vector coupling. The "minimum" coupling yields the smallest possible vector LQ_1 production rate.

Even for minimum coupling, the mass limit contour is more stringent than for the scalar case.

Limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings.
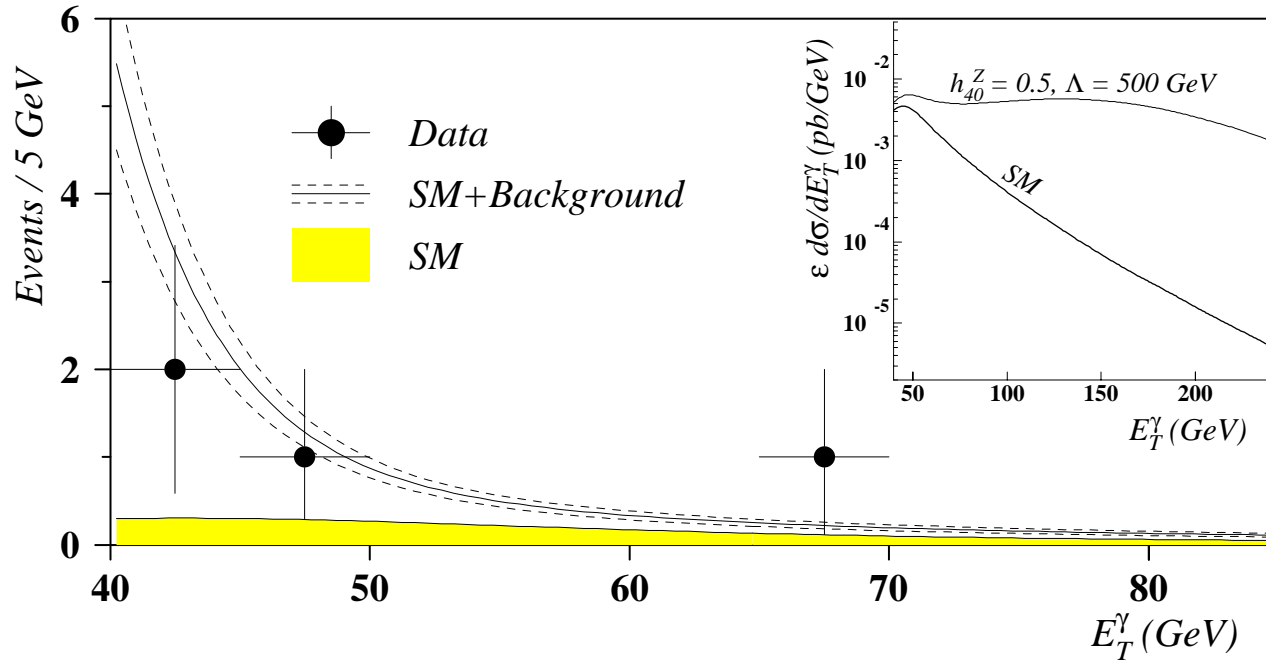
In the SM, both the $ZZ\gamma$ and $Z\gamma\gamma$ couplings vanish. CP-conserving anomalous $ZV\gamma$ couplings $h_{30}{}^V$ and $h_{40}{}^V$ correspond to the E1 and M2 transition moments of the $ZV\gamma$ vertex. To obey unitarity, they are multiplied by $(1 + \bar{s}/\Lambda^2)^{-n}$, where n is h's first subscript.

The main limit on these anomalous couplings comes from the non-observation by D0, above background and SM radiative effects, of $Z\gamma$ production in which $Z \to \nu\nu$, giving a γ + missing energy signature.

Shown are D0's combined limits on $h_{30}{}^V$ and $h_{40}{}^V$.
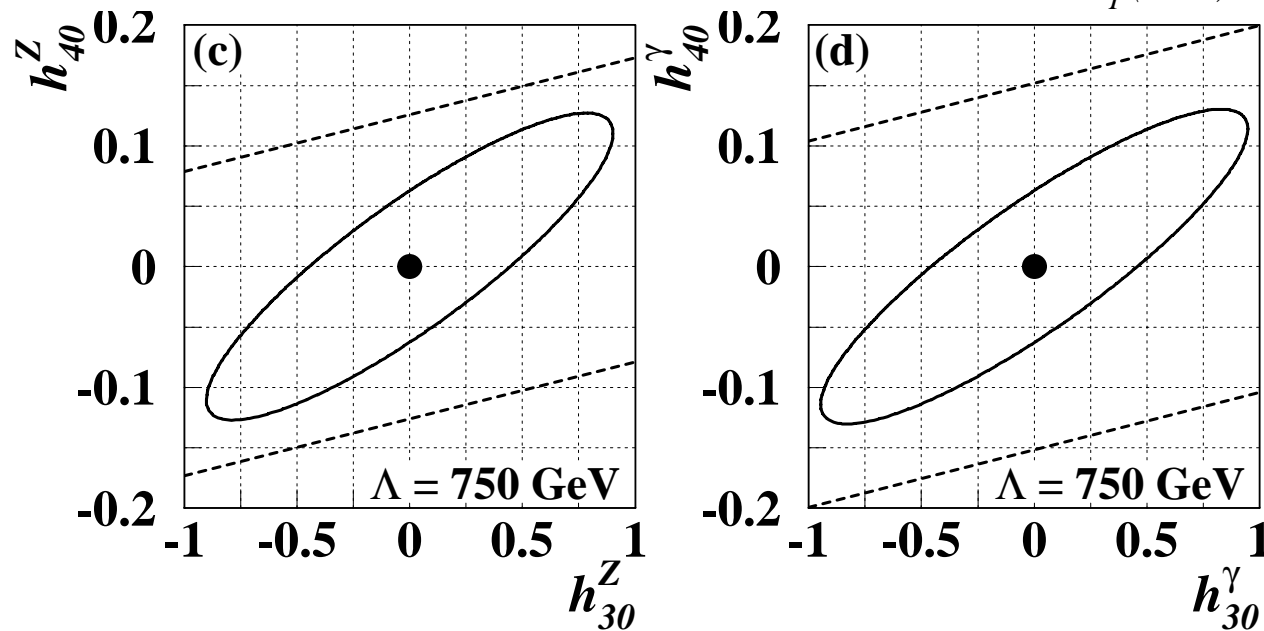
Limits on Z' mass and mixing in extended gauge models

New heavy gauge bosons are expected if the Standard Model is extended by additional gauge symmetries. These extensions are motivated *e.g.* by grand unified theories or by compactified string models.

An example is the decomposition

$$E_6 \to U(1)_\psi \times SO(10) \to U(1)_\psi \times U(1)_\chi \times SU(5) \to U(1)_{\theta(E6)} \times \text{SM} .$$

The Z' boson originating from this new $U(1)$ symmetry is labeled by the angle β_E by which $U(1)_\chi$ and the $U(1)_\psi$ mix to form it. Often-studied cases are

$$\theta(E6) = 0 \quad (\text{model ``}\chi\text{''})$$
$$\theta(E6) = \pi/2 \quad (\text{model ``}\psi\text{''})$$
$$\theta(E6) = \arctan(-\sqrt{5}/3) \quad (\text{model ``}\eta\text{''})$$
$$\theta(E6) = \arctan(\sqrt{15}) \quad (\text{model ``}\nu\text{''}) .$$

The Z'-fermion couplings for these models are prescribed within a range, with the upper bound usually taken.

As another example, the left-right model

$$SO(10) \to U(1)_{B\text{-}L} \times SU(2)_R \times SU(2)_L \times SU(3)_C \quad (\text{model ``LR''})$$

has a Z' with fermion couplings fixed by manifest L-R symmetry. Another ("ALR") left-right prescription originates from E_6 GUTs. It has a nonstandard W_R and different Z'-fermion couplings.

Finally, experimenters often refer to a toy "SSM" model in which the Z' couplings are identical to those of the Z.

Limits on Z' mass and mixing in extended gauge models (cont'd)

The above described models fail to span a reasonable set of possibilities:

"Kinetic mixing" can shift the couplings. Its term in the Lagrangian has a factor $\sin \chi$, which these models take to be zero.

String theorists describe a broader class of models with additional $U(1)$ factors.

At the (physical) Z_1 pole, e^+e^- experiments are sensitive mainly to the presence of a nonzero mixing angle θ_M between the (SM) Z and Z' yielding the Z_1. [Making specific assumptions involving the Z-Z' mass matrix, limits on θ_M can be re-expressed as limits on $M(Z')$ when $M(Z') \gg M(Z)$.]

The chief experimental constraints at the Z_1 pole are the hadron and lepton-pair cross sections and the lepton forward-backward and left-right asymmetries.

When cross sections and forward-backward asymmetries well above the Z_1 pole from LEP 2 are included, sensitivity independently to both θ_M and $M(Z')$ can be achieved.

Limits on Z' mass and mixing in extended gauge models (cont'd)

L3 make a preliminary fit to their LEP1 and LEP2 cross sections and lepton asymmetries, using ZEFIT, an extension to ZFITTER.

95% CL preliminary limits in the $\theta_M - M(Z')$ plane are obtained for the χ and ψ models...
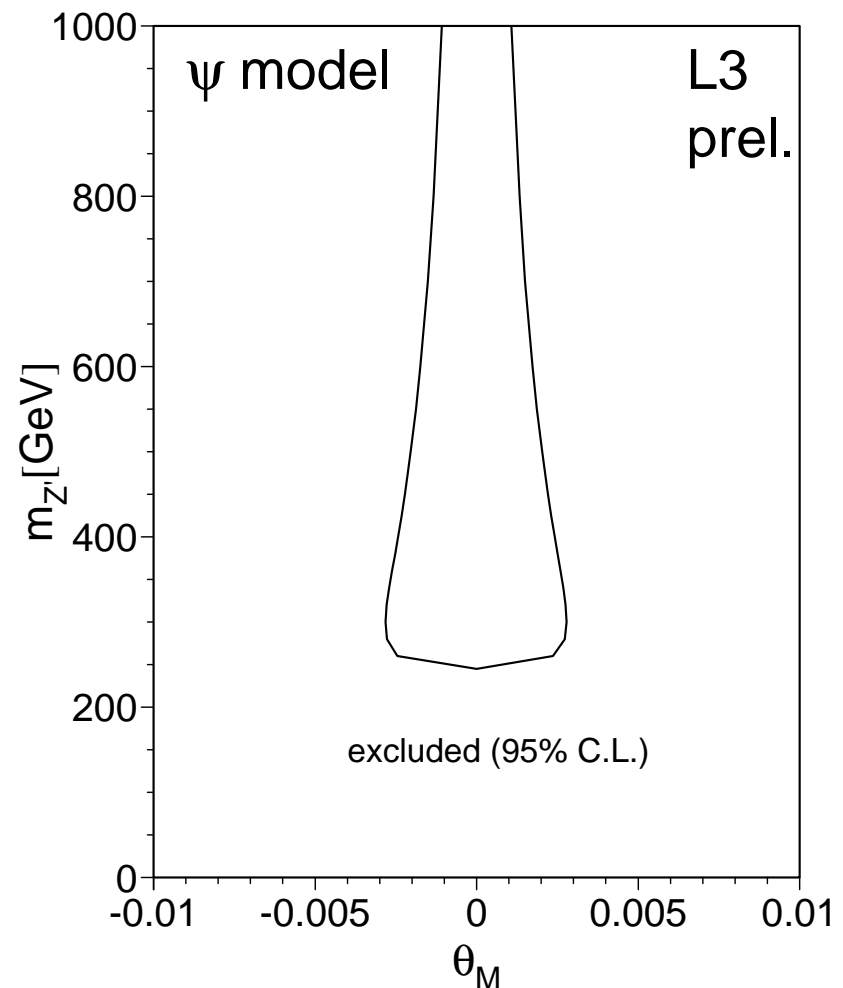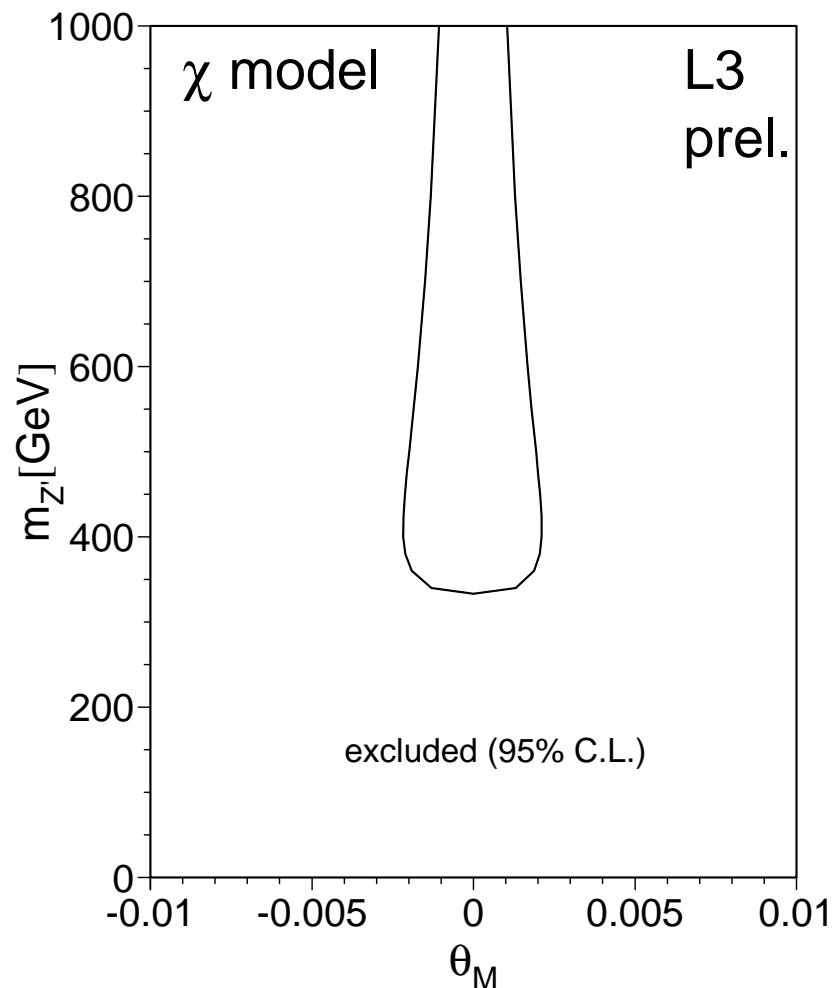
Limits on Z' mass and mixing in extended gauge models (cont'd)

...and for the η and LR models.

The preliminary L3 limits on θ_M are competitive with recent fits to world data. However, except for the toy "SSM" model, for which they obtain $M(Z') > 805$ GeV, L3 limits on $M(Z')$ are weaker than those available from Tevatron searches.

Limits on Z' mass and mixing in extended gauge models (cont'd)

Limits on Z' production(95% C.L.)

$\sigma \cdot B$ predicted using SM couplings

Phys. Rev. D 51, R949 (1995) (CDF ee, 19.7pb^{-1})

505 GeV/c^2

690 GeV/c^2

95% C.L. $\sigma \cdot B$ limit (CDF ee+$\mu\mu$, 110pb^{-1})

$\sigma \cdot B(Z' \rightarrow \text{dileptons})$ [pb]

Z' Mass (GeV/c^2)

DØ Preliminary (104 pb^{-1})

$\eta < 1.0$ and $\Delta\eta < 1.6$

$M_{Z'} > \sim 615$ GeV/c^2

$M_{Z'} < \sim 365$ GeV/c^2

- - - - Z' σ x BR x acceptance

$\sigma \times BR \times a$ (pb)

$M_{Z'}$ (GeV/c^2)
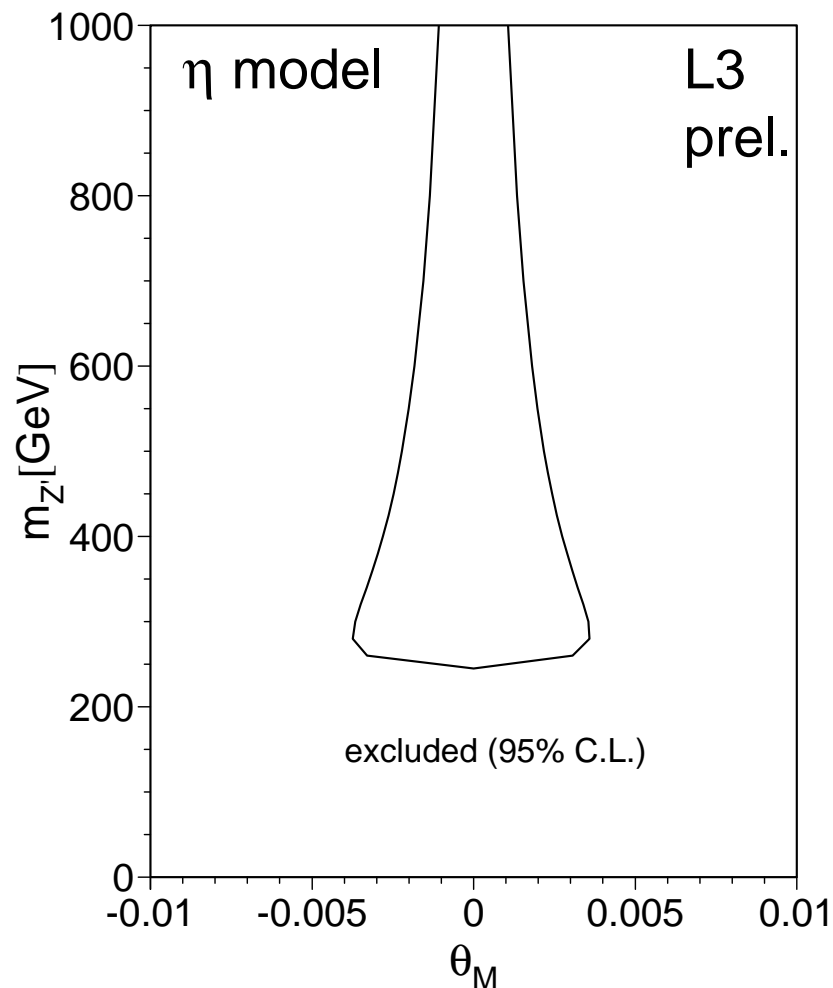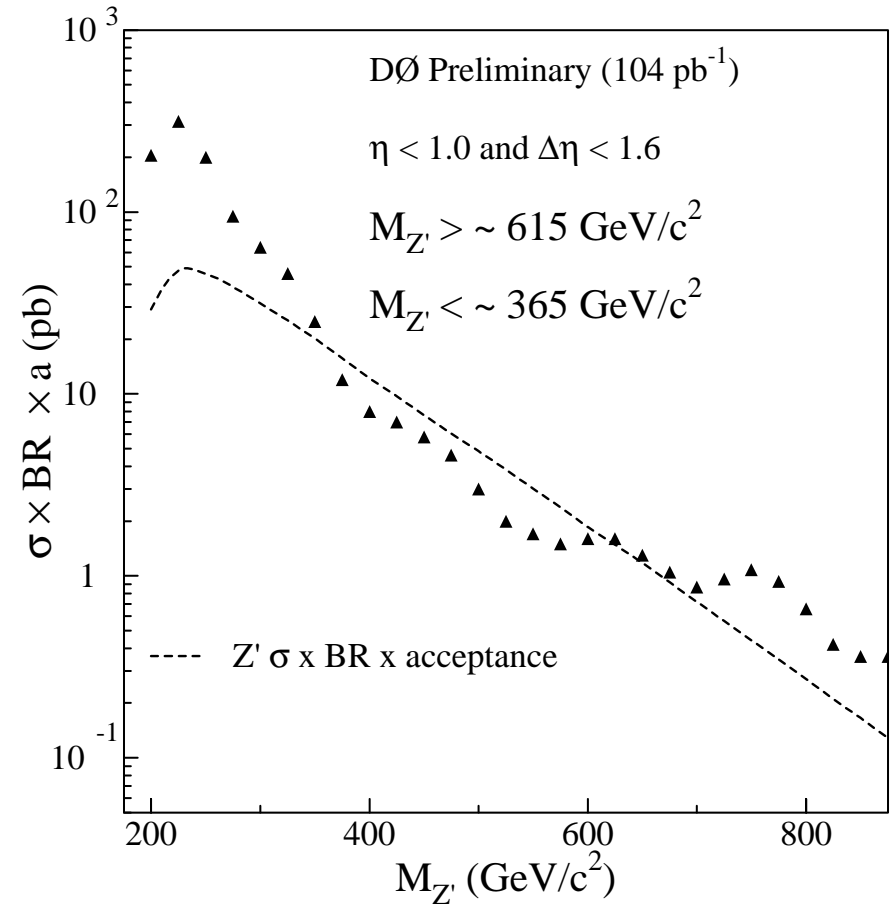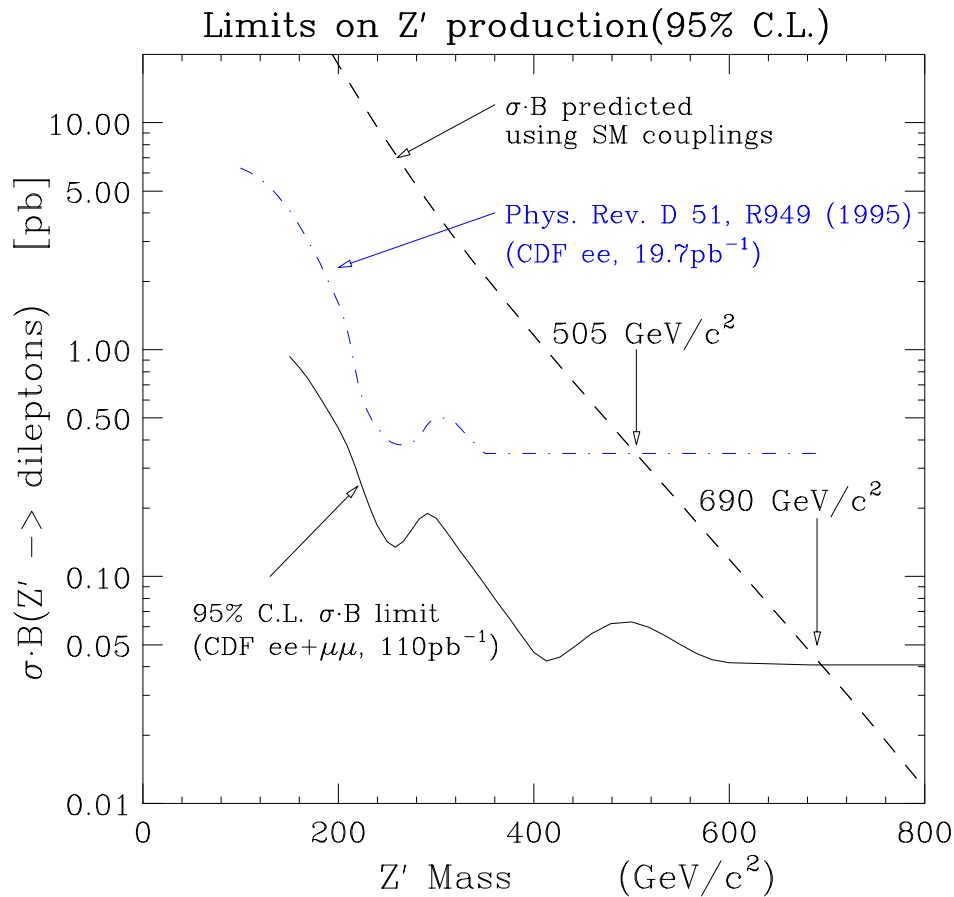
At the Tevatron, direct searches for $Z' \rightarrow e^+e^-$ and $\mu^+\mu^-$ yield limits on $M(Z')$ that do not vary widely among the various models.

Displayed are the $\sigma \times B$ limits from CDF as a function of dilepton mass (left), and from D0 as a function of dijet mass (right). The latter constrains a possible "leptophobic" Z' with SM couplings.

Limits on Z' mass and mixing in extended gauge models (cont'd)

CDF's $M(Z')$ limits (left) for a variety of models are published; the areas beneath the lines are excluded. D0's Z' searches (right) are preliminary. The region between the "leptophobic" dashed lines is excluded by nonobservation of a bump in D0's dijet mass spectrum.
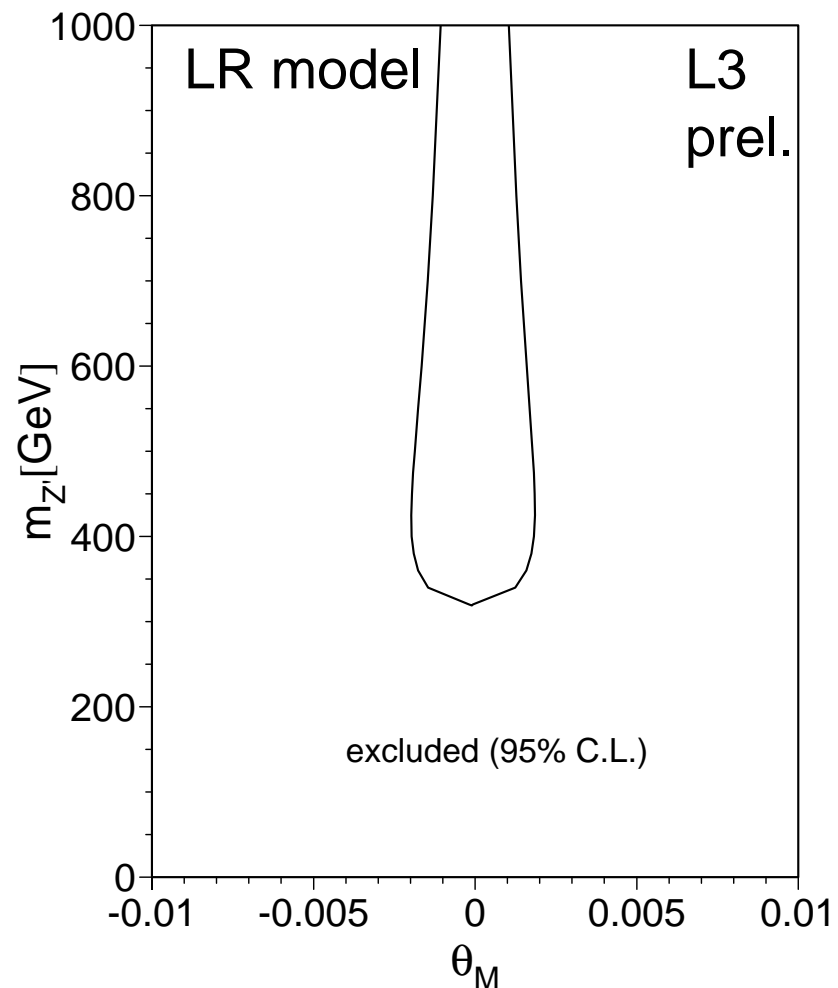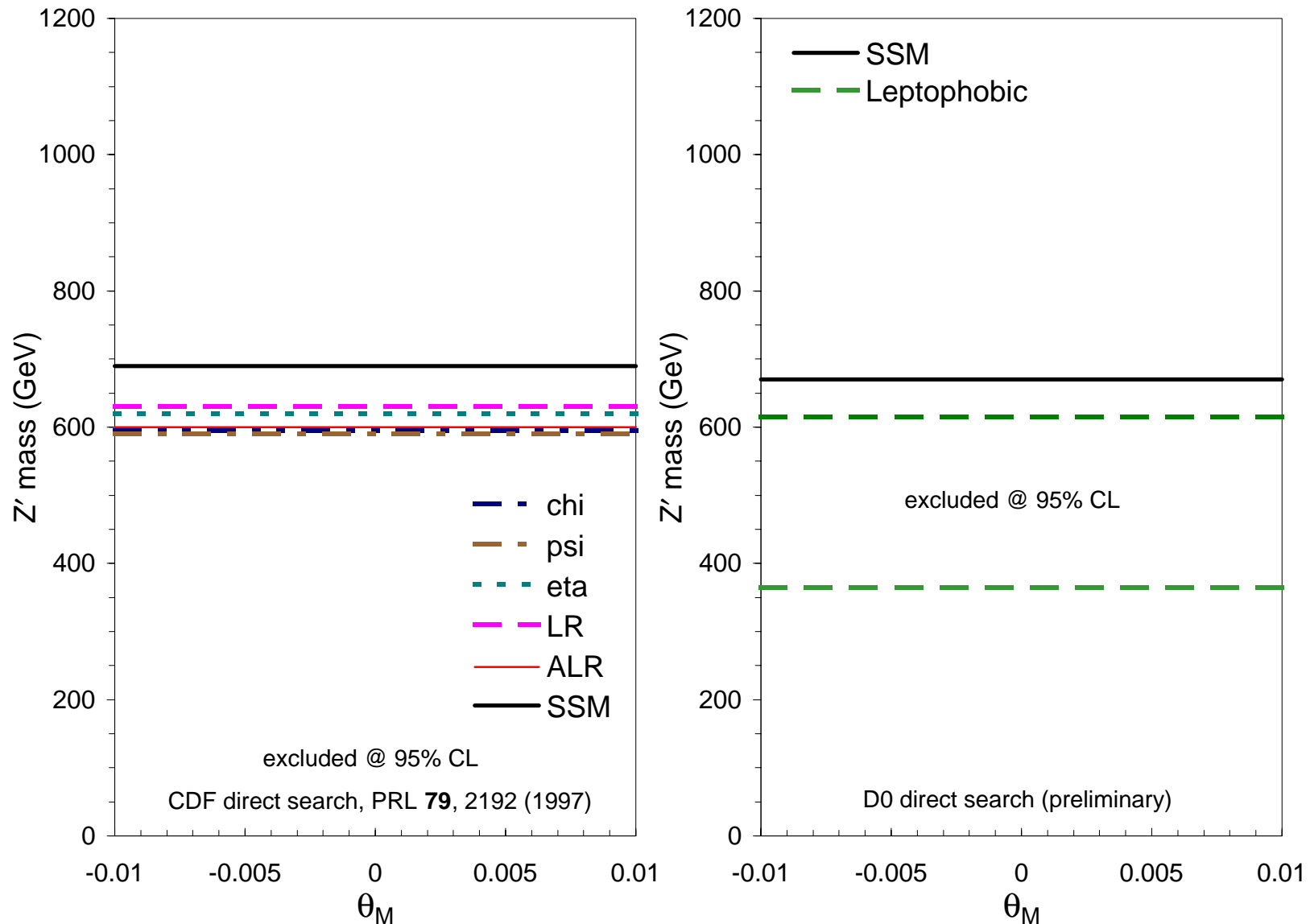
Limits on Z' mass and mixing in extended gauge models (cont'd)

Except for the toy "SSM" case, the just displayed Tevatron mass limits are stronger than are obtained from recent fits to all indirect constraints, including low-energy weak neutral current processes.
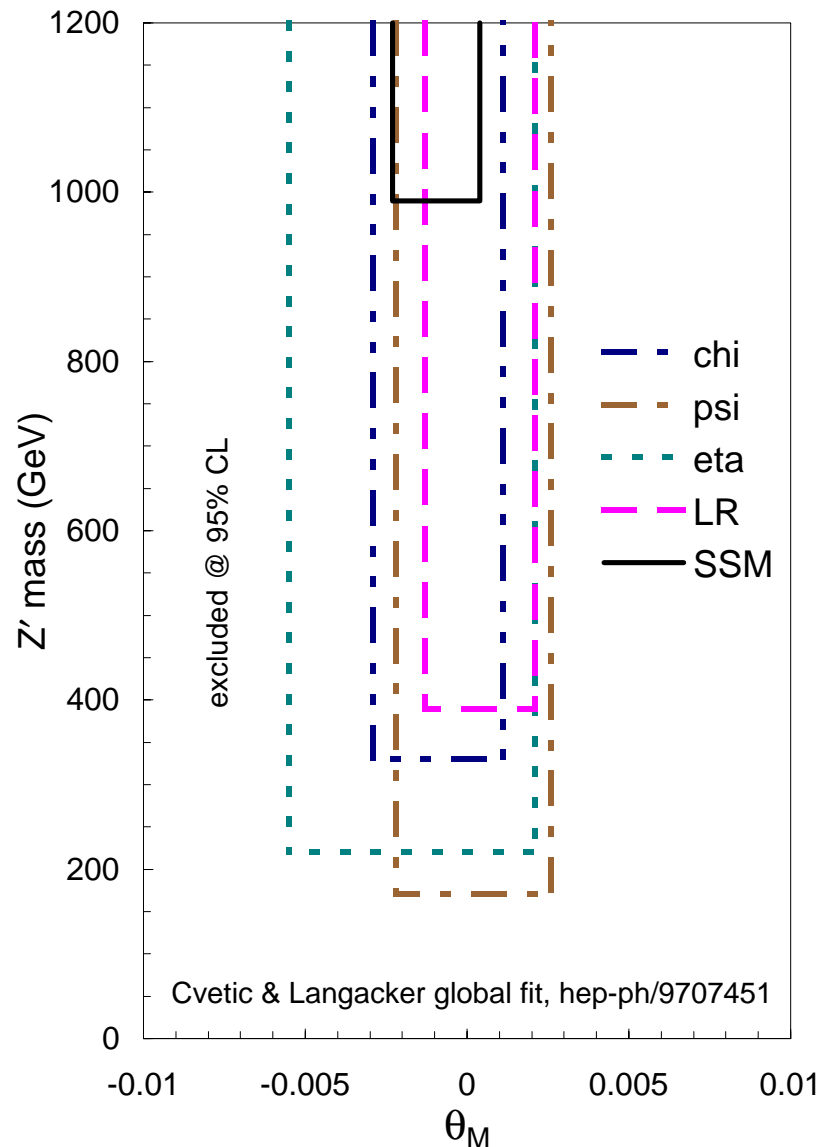
Plotted on the same scale is the result of Cvetic and Langacker's 1997 fit to all available data, excluding direct Tevatron searches and LEP 2 data, but including low-energy constraints that are outside the scope of this review.

The $M(Z')$ limits are for the case in which no assumption is made on the $U(1)'$ charges. In the χ and LR models, respectively, if definite $U(1)'$ charges are assumed, much higher minimum Z' masses of 1160 and 1680 GeV are obtained.

Cvetic & Langacker global fit, hep-ph/9707451

Limits on Z' mass and mixing in extended gauge models (cont'd)

Z' mass (GeV) vs θ_M

excluded @ 95% CL

- — · — chi
- — · — psi
- · · · · eta
- — — nu

Cho Hagiwara Umeda global fit, hep-ph/9805448
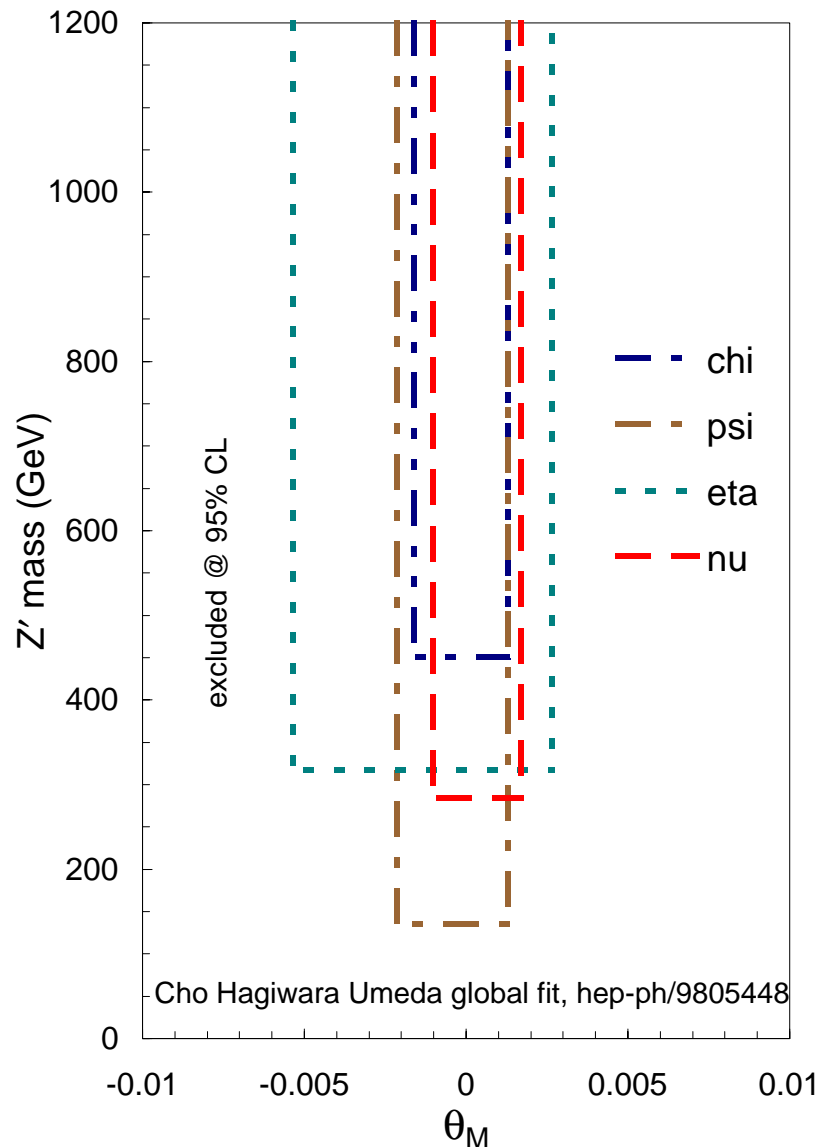
Also plotted are the results of the more general May 1998 fit of Cho, Hagiwara, and Umeda to data similar to those used by Cvetic and Langacker.

To put this plot on the common scale, Cho *et al.*'s mixing angle limits were divided by ($\sqrt{5/3} \times \sin\theta_W$).

When definite $U(1)'$ charges are assumed and other parameters are varied, minimum Z' masses are obtained for all models. Compared to those in the plot, most of these mass limits are far stronger, of order 1-2 TeV. These are still below the LHC discovery limits (~3 TeV).

Limits on Z' mass and mixing in extended gauge models (cont'd)

		pull = $\frac{\langle \text{data}\rangle - \text{best fit}}{\langle \text{error}\rangle}$					
		SM	χ	ψ	η	ν	η^*
Z-pole experiments							
m_Z (GeV)	91.1867±0.0020						
Γ_Z (GeV)	2.4948 ± 0.0025	−0.8	−0.8	−0.6	−0.7	−0.7	−0.6
σ_h^0(nb)	41.486 ± 0.053	0.3	0.6	0.6	0.3	0.6	0.2
R_ℓ	20.775 ± 0.027	0.9	0.8	0.7	0.9	0.7	1.1
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	0.8	0.8	0.7	0.7	0.8	0.7
A_τ	0.1411 ± 0.0064	−1.0	−1.0	−1.0	−1.0	−1.0	−1.0
A_e	0.1399 ± 0.0073	−1.1	−1.0	−1.1	−1.1	−1.1	−1.1
R_b	0.2170 ± 0.0009	1.4	1.4	1.5	1.4	1.4	0.6
R_c	0.1734 ± 0.0048	0.3	0.3	0.2	0.3	0.3	0.5
$A_{FB}^{0,b}$	0.0984 ± 0.0024	−2.1	−2.0	−2.1	−2.1	−2.1	−2.2
$A_{FB}^{0,c}$	0.0741 ± 0.0048	0.0	0.1	0.0	0.0	0.0	−0.1
A_{LR}^0	0.1547 ± 0.0032	2.2	2.3	2.2	2.2	2.2	2.2
A_b	0.900 ± 0.050	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7
A_c	0.650 ± 0.058	−0.3	−0.3	−0.3	−0.3	−0.3	−0.4
W-mass measurement							
m_W (GeV)	80.43 ± 0.084	0.5	0.5	0.5	0.5	0.5	0.5
$\chi^2_{\min}$ and d.o.f.							
$\chi^2_{\min}$		16.9	16.7	16.7	16.9	16.6	16.1
d.o.f.		14	12	12	12	12	12
parameters	constraints	best fit values					
m_t (GeV)	175.6 ± 5.5	172.4	173.1	172.8	172.3	172.9	172.9
$\alpha_s(m_{Z_1})$	0.118 ± 0.003	0.1185	0.1179	0.1180	0.1185	0.1179	0.1192
$1/\bar{\alpha}(m^2_{Z_1})$	128.75 ± 0.09	128.75	128.76	128.74	128.74	128.75	128.74
T_{new}	——	——	0	0	0	0	0
$\bar{\xi}$	——	——	0.0002	0.0002	−0.0001	0.0002	0.0027

		pull = $\frac{\langle \text{data}\rangle - \text{best fit}}{\langle \text{error}\rangle}$					
		SM	χ	ψ	η	ν	η^*
LENC experiments							
A_{SLAC}	0.80 ± 0.058	1.0	1.0	1.0	1.0	1.0	0.9
A_{CERN}	−1.57 ± 0.38	−0.4	−0.4	−0.4	−0.4	−0.4	−0.4
A_{Bates}	−0.137 ± 0.033	0.5	0.4	0.4	0.4	0.4	0.5
A_{Mainz}	−0.94 ± 0.19	−0.3	−0.3	−0.3	−0.4	−0.3	−0.3
$Q_W(^{133}_{55}Cs)$	−72.08 ± 0.92	1.0	−0.2	1.0	0.2	−0.1	1.3
K_{FH}	0.3247 ± 0.0040	−1.5	−1.4	−1.5	−1.5	−1.4	−1.4
K_{CCFR}	0.5820 ± 0.0049	−0.5	−0.4	−0.3	−0.4	−0.4	−0.5
$g_{LL}^{\nu_\mu e}$	−0.269 ± 0.011	0.4	0.1	0.1	0.5	0.1	0.4
$g_{LR}^{\nu_\mu e}$	0.234 ± 0.011	0.1	0.0	0.4	0.2	0.2	0.1
$\chi^2_{\min}$ and d.o.f.							
$\chi^2_{\min}$		22.0	20.2	21.5	21.2	20.4	21.7
d.o.f.		23	20	20	20	20	21
parameters	constraints	best fit values					
m_t (GeV)	175.6 ± 5.5	171.6	172.3	172.1	171.5	172.3	172.0
$\alpha_s(m_{Z_1})$	0.118 ± 0.003	0.1185	0.1181	0.1181	0.1185	0.1181	0.1189
$1/\bar{\alpha}(m_{Z_1})$	128.75 ± 0.09	128.75	128.75	128.75	128.73	128.75	128.75
T_{new}	——		0.0	0.0	0.0	0.0	0.0
$\bar{\xi}$			0.0001	0.0002	−0.0003	0.0001	0.0016
$g_E^2/c_\chi^2 m^2_{Z_E}$			0.279	1.771	−0.646	0.668	——

For completeness, the inputs and other details of Cho *et al.*'s fit are shown. The first fit uses the results of Z-pole experiments together with measurements of the *W* and top masses, and of α_s and α.
It constrains mainly the *Z-Z'* mixing angle and the *T* parameter.

The second fit adds low-energy neutral current measurements. Sensitivity to the *Z'* mass through a contact term is gained, along with modest additional constraints on the other parameters.

Limits on contact interactions

At $s << M^2(Z')$, Z' exchange would represent one form of effective four-fermion contact interaction. The contact interaction scale parametrizes searches for quark and lepton compositeness.

The vector contact Lagrangian has terms of the form

$$\eta_{HH'}\,(\,\bar{f}_H\gamma_\mu f_H\,)\,(\,\bar{f}_{H'}'\,\gamma^\mu f_{H'}'\,)$$

where $f f f' f'$ are the four fermions involved, and H and H' run over chiralities L, R.

[Tensor *eeff* contact interactions with $\Lambda < 130$ TeV and scalar *eeee* contact interactions with $\Lambda < 45$ TeV are ruled out by p_e limits, and tensor *qq*μμ or μμττ contact interactions with $\Lambda < 16$ TeV are ruled out by $(g_\mu$-2). So high energy experiments focus mainly on vector terms.]

We consider vector contact interactions involving fermions *qqqq*, *llqq*, *eeqq*, ννqq, νν*e*μ, and *eell*, where *q* (*l*) assigns the same contact interaction to all quarks (charged leptons).

For each fermion set, the limits are described further by the assumed relative magnitudes of the coefficients (η_{LL},η_{LR},η_{RL},η_{RR}). We consider the cases **LL** (1,0,0,0), **LL+RR** (1,0,0,1), **LR** (0,1,0,0), **LR+RL** (0,1,1,0), **LL−LR** (1,−1,0,0), **VV** (1,1,1,1), and **AA** (1,−1,−1,1). (Typically the limits for **RR** (**RL**) [**RL−RR**] are similar to those for **LL** (**LR**) [**LL−LR**].)

Atomic parity violation places severe constraints [$\Lambda > O(10$ TeV)] on Lagrangians for which the sum $\eta_{LL} + \eta_{LR} - \eta_{RL} - \eta_{RR}$ does not vanish. So we include the cases **LL** and **LR** only for comparing experimental sensitivities.

95% single-sided confidence lower limits $\Lambda+$ and $\Lambda-$ are set on the energy scale for each case, corresponding to whether the first nonvanishing η is positive or negative.

Limits on contact interactions (cont'd)

chirality		LL ♥♣ Λ+	Λ−	LL+RR Λ+	Λ−	LR ♥♥♣ Λ+	Λ−	LR+RL Λ+	Λ−	LL−LR ♥♥♥ Λ+	Λ−	VV Λ+	Λ−	AA Λ+	Λ−
qqqq	D0	2.1	1.9												
	CDF	1.8	1.6												
llqq	CDF	3.1	4.3			3.3	3.9					5.0	6.3	4.5	5.6
eeqq	D0♠	3.3	4.2			3.4	3.6					4.9	6.1	4.7	5.5
	CDF	2.5	3.7			2.8	3.3					3.5	5.2	3.8	4.8
	OPAL 183♠	4.4	2.8	4.4	3.8	3.3	3.6	3.1	5.5			4.1	5.7	6.3	3.8
	L3 172	3.0	2.1	3.2	2.8	2.4	2.6	2.4	3.7			3.2	3.9	4.3	2.9
	ALEPH 183♠	3.9	2.7	4.1	3.6	2.1	3.4	3.0	4.9			4.0	5.2	5.6	3.7
	ZEUS♠			2.8	1.5			4.5	4.1	1.8	3.0	4.9	4.6	2.0	4.0
	Gonzalez *et al*	3.3	3.7	3.0	3.4	3.4	3.0	3.0	2.7			1.1	1.2	4.3	4.8
	Barger *et al*							3.5	5.3	3.5	3.8	4.1	6.9	4.4	4.7
vv qq	CCFR	4.7	5.1			4.2	4.4					8.0	8.3	3.7	5.9
vv e μ	TRIUMF E185					3.1♦		3.1♦		3.1♦					
eell	OPAL 183♠	5.2	5.3	7.2	7.4	5.6	5.2	7.8	7.3			9.6	9.3	7.7	8.3
	L3 172	4.0	3.1	5.5	4.4	3.4	4.0	4.8	4.3			7.1	5.8	4.9	4.1
	ALEPH 183♠	6.1	5.4	8.4	7.5	6.5	5.2	9.4	7.4			11.8	9.4	8.2	9.0

♥**RR** typically similar. ♥♥**RL** typically similar. ♥♥♥**RL−RR** typically similar.

♣Severe atomic parity violation constraints exist. ♠Preliminary. ♦If $v_R > 20$ MeV/c^2 or nonexistent.

Gonzalez-Garcia, Gusso, and Novaes (hep-ph/9802254) obtain limits from LEP/SLD $\Gamma_l(Z)$ using a one-loop calculation.

Barger, Cheung, Hagiwara and Zeppenfeld (hep-ph/9707412) fit mid '97 world data at low, medium, and high energies.

Limits on contact interactions (cont'd)
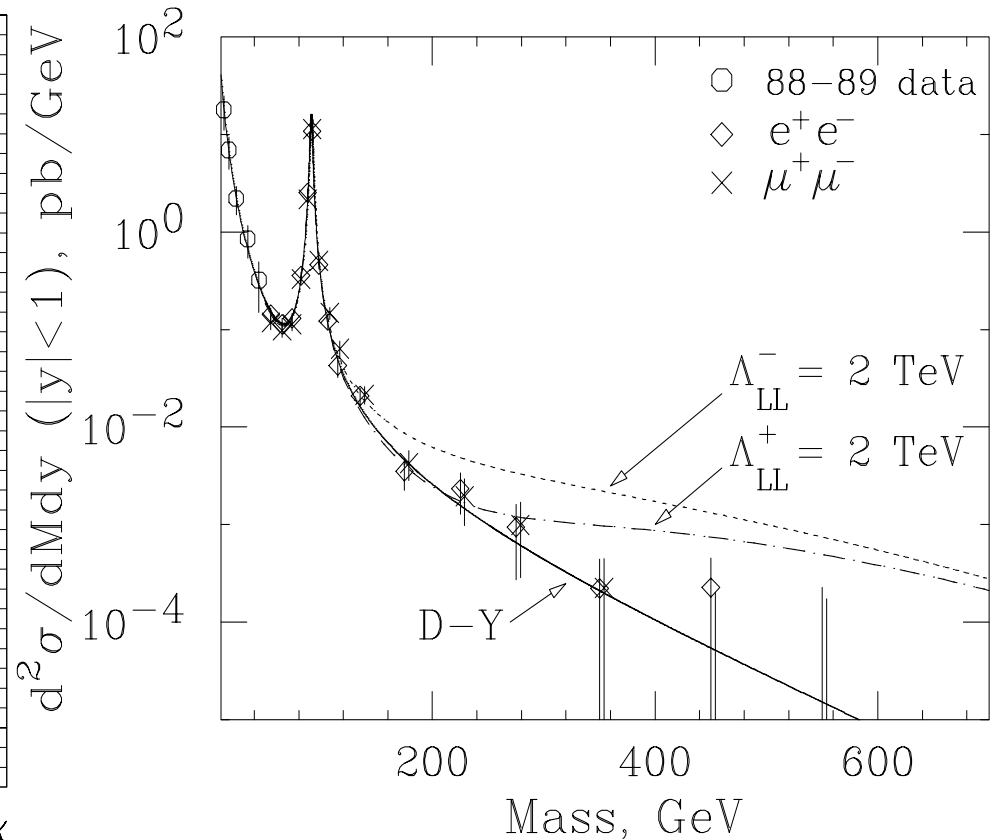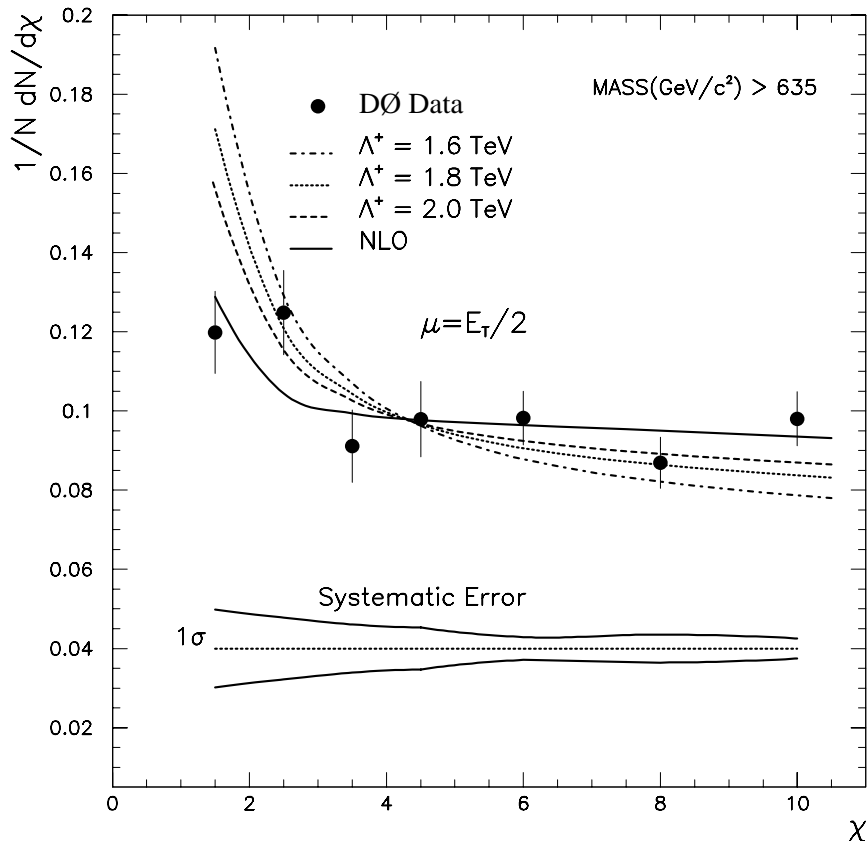
The best limits on quark compositeness (***qqqq***) result from D0's measurement of the dijet angular distribution.

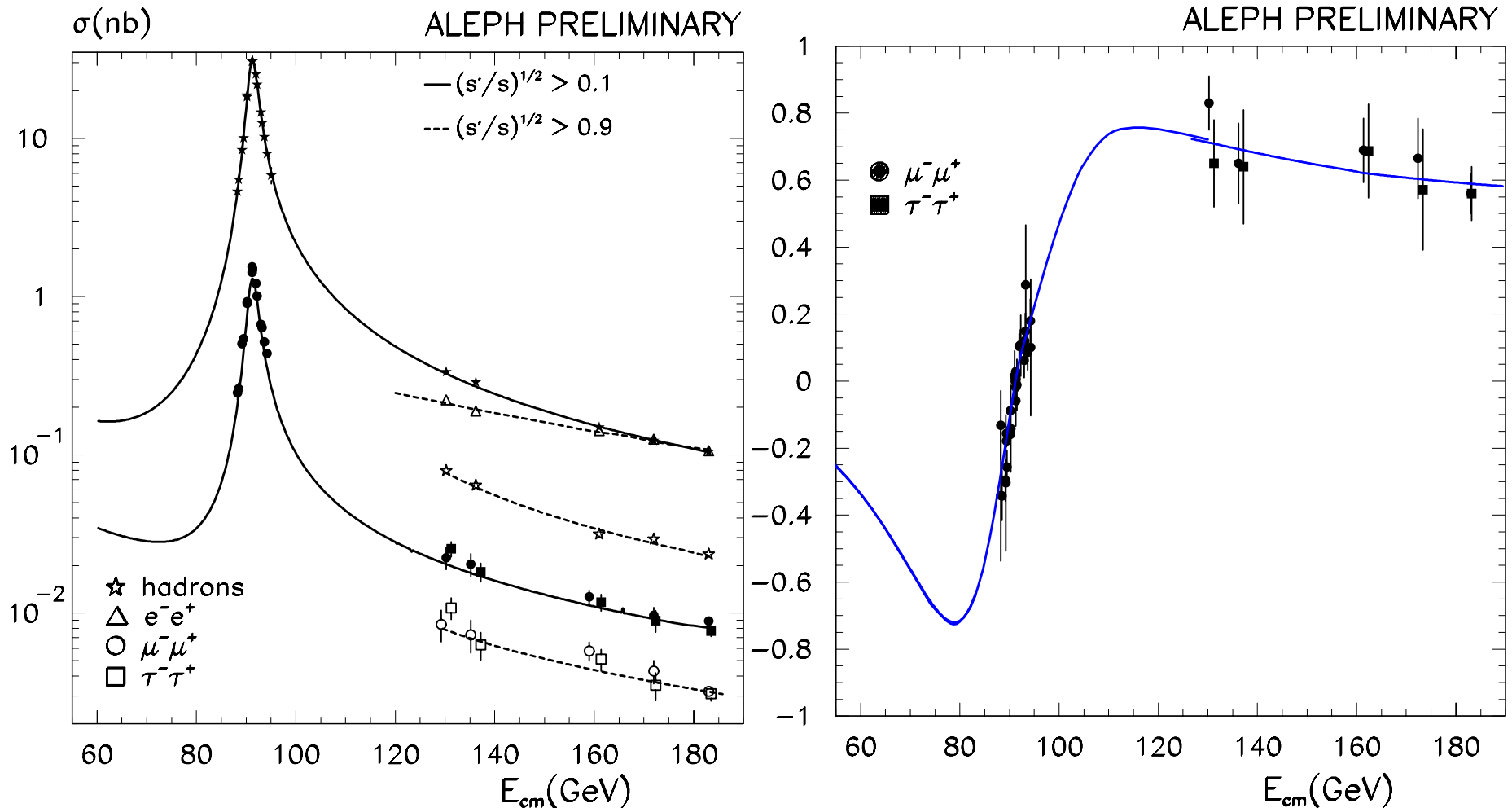Rutherford scattering is flat in the variable χ ($\chi = 1$ when $\theta^* = 90°$).

Contact interactions would be more central than t-channel gluon exchange. An enhancement near $\chi = 1$ would result.

Important constraints on quark-lepton compositeness (***llqq***) result from CDF's study of Drell-Yan ee and $\mu\mu$ production.

For the limits quoted here, contact-interaction couplings to u and d quarks are assumed to be the same.

From these same data, a limit $\Lambda > 3.3$ GeV on the scale of ***llqq*** scalar couplings is obtained.

Limits on contact interactions (cont'd)

σ(nb) ALEPH PRELIMINARY

— $(s'/s)^{1/2} > 0.1$
--- $(s'/s)^{1/2} > 0.9$

☆ hadrons
△ e^-e^+
○ $\mu^-\mu^+$
□ $\tau^-\tau^+$

E_{cm}(GeV)

ALEPH PRELIMINARY

● $\mu^-\mu^+$
■ $\tau^-\tau^+$

E_{cm}(GeV)

At tree level at the Z_1 pole, (real) contact interactions do not interfere with (imaginary) electroweak processes, so experiments are insensitive to them. At one-loop level (Gonzalez-Garcia *et al.*), contact interactions do affect the leptonic Z width.

Above the Z_1 pole, especially including 183 GeV data, fermion pair cross sections (left) and angular distributions (A_{FB}, right) strongly limit *eeqq* and *eell* contact interaction scales.

Conclusions

The most recent (1997) data do not confirm the HERA high-Q^2 excesses.

So far, evidence is **not** found for:

First-generation leptoquarks below ~220 GeV, scalar or vector, with β=1 or 0.5, independent of *eq* coupling.

Anomalous *ZZγ* or *Zγγ* couplings.

Z′ masses below ~600 GeV, or *Z–Z′* mixing above ~2 mrad.

qqqq, *llqq*, *eeqq*, νν*qq*, νν*e*μ, or *eell* contact interactions, with *LL*, *LL+RR*, *LR*, *LR+RL*, *LL−LR*, *VV*, or *AA* couplings, at scales below ~2-10 TeV.

Many other possible new physics signals not addressed by this short review.

Experiments below as well as on the energy frontier continue to raise the thresholds for possible discovery of new high-mass phenomena.